Received 2005 June 10; Accepted 2005 September 2
Preprint typeset using LaTeX style emulateapj v. 11/26/03

POSSIBLE DETECTION OF LYMAN-α FLUORESCENCE FROM A DAMPED LYMAN-ALPHA SYSTEM AT REDSHIFT $Z \sim 2.8$[1]

Kurt L. Adelberger[2]
Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA, 91101

Charles C. Steidel
Palomar Observatory, Caltech 105–24, Pasadena, CA 91125

Juna A. Kollmeier
Department of Astronomy, Ohio State University, McPherson Laboratory, 140 West 18th Avenue, Columbus, OH 43210

Naveen A. Reddy
Palomar Observatory, Caltech 105–24, Pasadena, CA 91125

Draft version February 5, 2008

ABSTRACT

We have detected Lyman-α emission from a damped Lyman-alpha system (DLA) that lies near the bright quasar HS1549+1919. The DLA has the same redshift as HS1549+1919 and was discovered in the spectrum of a faint QSO that lies $49''$ away (380 proper kpc). The emission line's luminosity, double-peaked profile, and small spatial separation from the DLA suggest that it may be fluorescent Lyman-α emission from gas that is absorbing the nearby QSO's radiation. If this is the case, our observations show that the DLA has a size of at least $1''.5$ and that the QSO's luminosity one million years ago was similar to its luminosity today. A survey for similar systems within $\sim 1'$ of bright QSOs would put interesting limits on the mean quasar lifetime.

Subject headings: intergalactic medium — quasars: absorption lines

1. INTRODUCTION & DATA

Although best known for absorbing Lyman-α photons, intergalactic hydrogen also emits them, at the rate of about one Lyman-α photon for every two Lyman-continuum photons absorbed. Average intergalactic clouds absorb photons so slowly that their emission is almost undetectable (e.g., Hogan & Weymann 1987; Gould & Weinberg 1996), but optically thick clouds near QSOs should fluoresce far more brightly. While obtaining data for a survey of galaxies at redshifts $1.8 \lesssim z \lesssim 3.5$ along the line of sight to the bright QSO HS1549+1919 ($z \simeq 2.84$), we discovered what appears to be fluorescent Lyman-α emission from a DLA that lies near the QSO. We believe that this is the first detection of fluorescence from intergalactic gas.[3]

The damped Lyman-α system has redshift $z = 2.8420$ and column density $N_{\rm HI} = 2.5 \pm 0.5 \times 10^{20}$ cm^{-2}. We identified it in the spectrum of the Lyman-break object Q1549-D10 (magnitude $G_{\rm AB} = 23.7$; coordinates $\alpha_{2000} = 15^h51^m49^s.5$, $\delta_{2000} = 19^o10'41''$; redshift $z = 2.920$), which is a faint QSO that lies just $49''$ from the much brighter QSO HS1549+1919 ($G_{\rm AB} \sim 16$). The spectrum, shown in Figure 1, was obtained with 6 hours of integration time with the LRIS-B spectrograph (Steidel et al. 2004) in multislit mode on the Keck I telescope on 5 May 2005. Its resolution is ~ 3Å for point sources and ~ 5Å for extended sources. The slit width was $1''.2$. The redshift of the DLA appears to be the same as the redshift of HS1549+1919, $z_Q \sim 2.84$, although the QSO's redshift has been estimated from its broad emission lines and is therefore imprecise.[4]

The spectroscopic slit centered on Q1549-D10 had a length of $15''$. The two-dimensional spectrum shows a broad, double-peaked emission line roughly $1''.5$ to the east of Q1549-D10 (Figure 2). Comparing the line's spatial width ($0''.84$ FWHM) to the width of the nearby point source Q1549-D10 ($0''.72$ FWHM), we estimate an intrinsic size for the emitting region of roughly one-half arcsecond.[5] We interpret the emission as Lyman-α from the

[1] Based on data obtained at the W.M. Keck Observatory, which is operated as a scientific partnership between the California Institute of Technology, the University of California, and NASA, and was made possible by the generous financial support of the W.M. Keck Foundation.

[2] Carnegie Fellow

[3] The unique characteristic of the detection is the large distance (380 proper kpc, see below) between the fluorescent gas and the apparent source of the ionizing photons. Numerous authors have detected Lyman-α fluorescence from the gas that lies within the same halo as claimed ionizing source (e.g., Moller, Warren, & Fynbo 1998; Bergeron et al. 1999; Fynbo, Thomsen, & Moller 2000; Bunker et al. 2003; Moller, Fynbo, & Fall 2004; Weidinger et al. 2005).

[4] In June 2005, we used NIRSPEC on the Keck II telescope to measure a redshift of $z = 2.8443 \pm 0.0005$ for the QSO's MgII emission line. Richards et al. (2002) report that the mean difference between the velocity of MgII emission and a QSO's true recession velocity is 97 km s^{-1} and that the random scatter in the difference is 270 km s^{-1}. Neglecting the clustering of DLAs around QSOs, we consequently estimate a 1σ confidence interval for the difference between the QSO and DLA velocities of $\delta v = 80 \pm 270$ km s^{-1}.

[5] By repeatedly adding random noise to each pixel's observed flux and recalculating the widths of Q1549-D10 and the emitting region, we estimate a 90% confidence interval of $0''.3 < \Delta\theta < 0''.7$ for the emitting region's intrinsic (i.e., quadrature subtracted) FWHM.

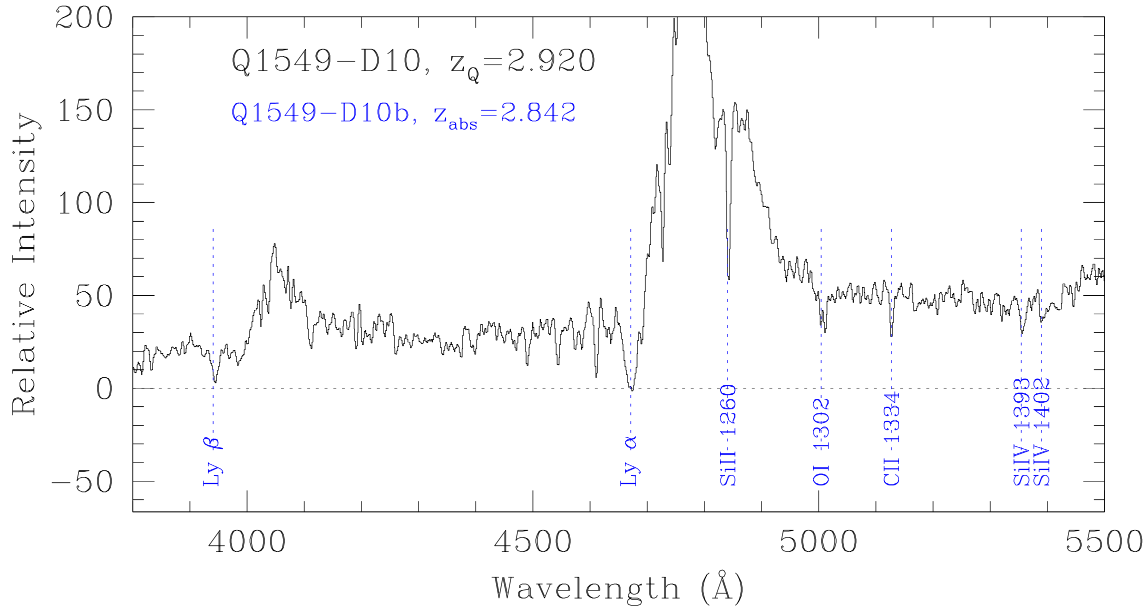

Fig. 1.— Spectrum of the QSO Q1549-D10 ($z = 2.920$). Absorption lines associated with the DLA at $z = 2.842$ are labeled.

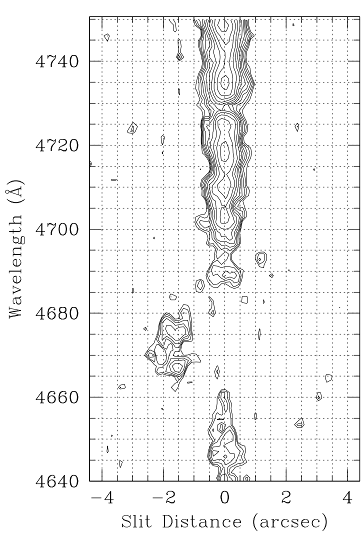

Fig. 2.— Two dimensional spectrum of D10. Wavelength increases from the bottom to the top of the figure, and spatial position varies from left to right. The damped Lyman-α absorption line in the QSO spectrum at $x = 0$, $\lambda \sim 4670$ is accompanied by an emission line with a small spatial offset.

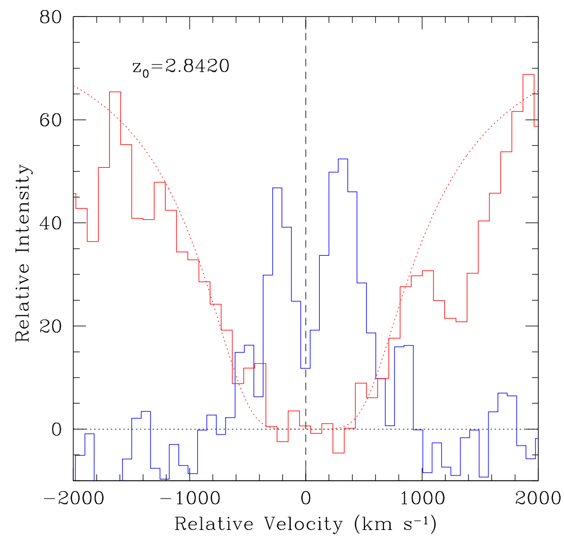

Fig. 3.— Velocity profiles of the double-peaked emission line and of the nearby damped absorption. Solid lines show our data; the dotted line shows our fit to the absorption profile. All velocities are relative to the DLA metal lines visible in Figure 1.

DLA, since its central wavelength is precisely what one would expect for Lyman-α at the redshift of the DLA's metal lines (Figure 3).

The relative spatial positions of HS1549+1919, Q1549-D10, and the Lyman-α emission region are shown in Figure 4. This is a section of a 2960-second G-band image that we obtained with LRIS-B on 6 April 2005. The U_n and $\mathcal{R}$ images discussed below were obtained on the same run, with exposure times of 3600s and 4800s respectively. Seeing was 0.″9 in each band.

2. INTERPRETATION

2.1. *Theoretical expectations for fluorescence*

The proximity of the DLA to HS1549+1919 suggests that the emission could be fluorescent, fueled by the absorption of the bright QSO's Lyman-continuum photons by the DLA's optically thick gas. If the Lyman-α emission were powered by the QSO, we would expect it to have the following three properties.

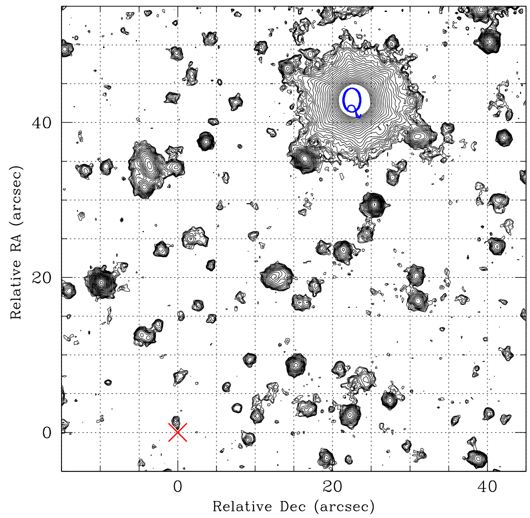

FIG. 4.— G-band image of the field. Q1549-D10, at position $(0,0)$, has been subtracted. The Lyman-α emitting region lies just above it on this plot. The bright QSO HS1549+1919 is labeled "Q".

(1) The Lyman-α line should have a width of roughly 8 times the velocity dispersion of the absorbing gas. Since Lyman-α photons can escape an optically thick cloud only when they are scattered away from the resonant frequency, the Lyman-α photons that emerge will come from the $\sim \pm 4\sigma$ wings of the Doppler profile (e.g., Zanstra 1949; Osterbrock 1962; Urbaniak & Wolfe 1981; Gould & Weinberg 1996; Zheng & Miralda-Escudé 2002b; cf. Cantalupo et al. 2005). The DLA's marginally resolved CII $\lambda 1334$ absorption line implies a velocity width of $\sigma \sim 60$ km s^{-1}, so the emission should be spread over a range of velocities $\Delta v \sim 500$ km s^{-1} if the absorbing gas has a velocity dispersion similar to the DLA's. The emission would emerge in two peaks with this separation if the gas were homogeneous and would be more continuously distributed throughout Δv otherwise. (The expected velocity dispersion would be significantly reduced, however, if all the ionizing photons were absorbed by a single cold clump orbiting in the DLA potential; see Gould & Weinberg 1996, Zheng & Miralda-Escudé 2002b, Cantalupo et al. 2005, and Kollmeier et al. 2005, in preparation, for further discussion.)

(2) The Lyman-α emission should emerge from the side of the DLA that lies closest to the QSO. According to Gould & Weinberg (1996; § 3), more than 98% of the Lyman-α photons will escape from the side the Lyman-continuum photons entered for column densities $N_{\rm HI} > 10^{20}$ cm^{-2}. Since the DLA will not begin to fluoresce brightly until the ionization front from the QSO has penetrated deeply into it, most of the way to the center, the fluorescent emission should emerge from near the center of the DLA. Shielded neutral gas should extend from the site of emission in the direction opposite the QSO. Figure 5 illustrates the situation. See the appendix for further discussion.

(3) Its surface brightness should be

$$\Phi = (1+z)^{-3}\eta_{\rm thick} F_c/\pi \tag{1}$$

where $\eta_{\rm thick} \simeq 0.6$ (e.g., Gould & Weinberg 1996) is the

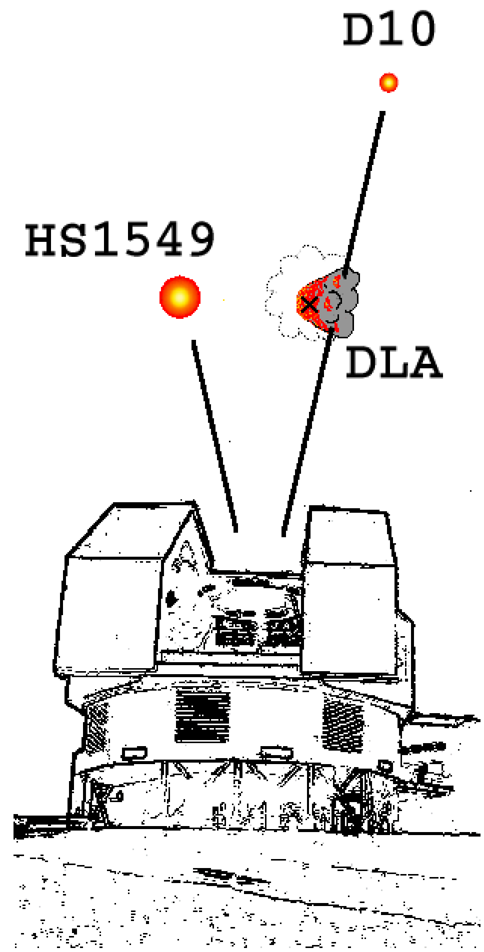

FIG. 5.— Cartoon view of the proposed geometry. The DLA's original size (dotted lines) has been reduced to the grey region by intense radiation from the nearby QSO HS1549+1919. Lyman-α fluorescence emerges from the side of the DLA that faces the QSO. This surface lies close to the stars at the original center of the DLA (black cross). Light from the background QSO Q1549-D10 passes through gas that is shielded from the QSO, and we observe damped absorption.

ratio of Lyman-α photons emitted to Lyman-continuum photons absorbed and F_c is the flux (cm^{-2} s^{-1}) of hydrogen-ionizing photons into the DLA. The following calculation implies that the expected fluorescent surface brightness is $\Phi \sim 2.7\times 10^{-5}$ photons cm^{-2} s^{-1} arcsec^{-2}, which implies a luminosity of $L \simeq 1.1\times 10^{-16}$ erg cm^{-2} s^{-1} if the fluorescing region has a size of 1 arcsec^2. Before the QSO's radiation hits, the ionizing flux is

$$F_c^0 = \pi \int_{\nu_0}^{\infty} d\nu \, \frac{J_{\rm bg}(\nu)}{h\nu} \tag{2}$$

where $J_{\rm bg}$ is the ambient radiation field. The value of F_c^0 is $\sim 1.6\times 10^5$ for plausible values of $J_{\rm bg}$, e.g., $J_{\rm bg} \sim 5\times 10^{-22}(h\nu/13.6{\rm eV})^{-1.8}$ erg s^{-1} cm^{-2} sr^{-1}, which we will assume throughout. After the radiation hits, the flux

will increase by the factor

$$g = 1 + \frac{10^{-0.4(48.60+m_{912})}}{(1+z)\pi J_{\rm bg}(c/912\text{Å})}\left[\frac{d_L(z)}{r_Q}\right]^2 \cos\theta, \quad (3)$$

where m_{912} is the QSO's AB magnitude at rest-frame 912Å, $d_L(z)$ is the luminosity distance to redshift z, r_Q is the proper distance between the DLA and QSO, $\theta < \pi/2$ is the angle between the vector to the QSO and the vector normal to the DLA's surface, and $J_{\rm bg}$ has units erg s^{-1} cm^{-2} Hz^{-1}. Equation 3 assumes that the spectra of the QSO and of the ambient radiation have the same shape shortwards of 912Å. Scaling a HIRES spectrum of HS1549+1919 (W. Sargent 2005, private communication) to match the QSO's observed U_n magnitude, $U_n = 16.9$, we estimate a continuum AB magnitude at 912Å of $m_{912} \simeq 16.7$. This implies $g \simeq 4850\cos\theta$ if the QSO and DLA have separation $49''$ and identical redshifts. For a spherical DLA with half-moon illumination, the effective value of g is $\langle g\rangle = 4g_{\rm max}(3\pi)^{-1}$, where $g_{\rm max}$ is the value of g for $\theta = 0$. We consequently adopt $g \sim 2000$. The value of Φ quoted at the beginning of the paragraph follows from inserting $F_c = gF_c^0$ into equation 1.

2.2. *Comparison to observations*

The observed characteristics of the Lyman-α line agree surprisingly well with these expectations. The line is broad, FWHM$\sim$ 990 km s^{-1}, and appears to consist of two peaks with separation $\Delta v = 530$ km s^{-1}. Its luminosity of $L = 2.1 \pm 0.5 \times 10^{-17}$ erg s^{-1} cm^{-2} and spatial extent of roughly one-half arcsecond imply a surface brightness similar to the expectation $\Phi = 1.1 \times 10^{-16}$ erg s^{-1} cm^{-2} arcsec^{-2}. The emission is produced by hydrogen that lies between the neutral gas in the spectrum of Q1549-D10 and the bright illuminating source HS1549+1919, and its offset from the neutral gas, $\sim 1''.5$, is consistent with theoretical expectations for the size of DLAs (e.g., McDonald & Miralda-Escudé 1999; Haehnelt, Steinmetz, & Rauch 2000; Zheng & Miralda-Escudé 2002a).

Although suggestive, the good agreement with these expectations does not prove that the Lyman-α emission is powered by the distant QSO. Similar emission-line characteristics could arise by chance if the line were powered by a local source. This possibility should be taken seriously, as we now show.

3. DISCUSSION

Our detection of the emitting region in the G and $\mathcal{R}$ bands (Figure 4; Table 1) implies that it has substantial luminosity in the continuum. Comparing its observed G-band magnitude, $G_{\rm AB} = 26.8 \pm 0.2$, to the flux detected in the emission line, we estimate that the observed-frame equivalent width of Lyman-α is $W_\lambda \sim 275 \pm 75$Å. This is several times smaller than would be expected if the emission were powered solely by the distant QSO (see, e.g., the calculation in the appendix). We are forced to conclude that the continuum receives a substantial contribution from some other source, presumably the stars that are associated with the DLA.

This does not contradict the idea that the Lyman-α line is powered primarily by fluorescence (cf. Fynbo, Thomsen, & Moller 2000). The DLA's strong metal lines imply that it ought to contain stars, and the calculation in the appendix suggests that the fluorescence should be produced by material that lies only $\sim 0''.1$ from the center of the DLA potential, which is presumably where any stars would be found. One could have anticipated its relatively small equivalent width.

Table 1. DLA characteristics

α(2000)[a]	δ(2000)[a]	$N_{\rm HI}$[b]	W_λ[c]	G[d]	$\mathcal{R}$[d]
15 51 49.6	19 10 41	2.5 ± 0.5	275 ± 75	26.8 ± 0.2	26.5 ± 0.2

[a]Coordinates of Lyman-α emitting region.
[b]Column density in the spectrum of Q1549-D10, 10^{20} cm^{-2}
[c]Observed-frame equivalent width of Ly-α emission, Å
[d]AB magnitude of the Lyman-α emitting region.

Could local emission from the DLA power the entire Lyman-α line? Although we cannot rule out the possibility, it seems implausible to us. First, this type of Lyman-α line is rarely produced by stars. Only 2% of randomly selected Lyman-break galaxies at this redshift have a Lyman-α emission line with so large an equivalent width (Steidel et al. 2000). Velocity widths FWHM $\sim$ 1000 km s^{-1} are observed only in the merging or active galaxies of the Lyman-break sample, and we see no sign of either the rapid star formation that would accompany the former or the other broad emission lines (CIV, etc.) that would accompany the latter. Although broad and strong Lyman-α lines are (not surprisingly) more common among galaxies discovered in Lyman-α surveys (e.g., Francis et al. 2004), fluorescence remains the best explanation for the observed double-peaked profile. Second, regardless of its stellar content, the DLA is optically thick to Lyman-continuum photons and lies near a very bright source. It is guaranteed to fluoresce unless the QSO's radiation is beamed or has not yet had time to reach it.

Isotropically emitted Lyman-continuum photons from the QSO will have reached the DLA at the time of observation as long as the QSO was shining at the earlier time $\Delta t = [(R^2 + Z^2)^{1/2} + Z]/c$, where $R \equiv D_A(\bar{z})\theta$ and $Z \equiv [D_C(z_{\rm DLA}) - D_C(z_Q)]/(1+\bar{z})$ are the proper separations of the QSO and DLA perpendicular and parallel to the line of sight, D_A is the angular diameter distance, $D_C(z)$ is the comoving distance to redshift z, and $\bar{z} \equiv (z_{\rm DLA} + z_Q)/2$ (e.g., Adelberger 2004). If the DLA and QSO have exactly the same redshift, so that $Z = 0$, then photons will reach the DLA roughly 1.2 Myr after they were emitted. Since the DLA will probably not begin to fluoresce brightly until ~ 0.1 Myr after it is first illuminated (see the appendix), we would expect to see fluorescent emission as long as the QSO has been radiating for at least 1.3 Myr. The minimum lifetime could be somewhat longer or shorter, depending on the actual value of Z, but if Z were significantly different from 0 the luminosity of the Lyman-α line would be too large to be explained by the QSO's radiation.[6]

[6] The nominal 1σ uncertainty in the velocity difference between the QSO and DLA, 270 km s^{-1} (Richards et al. 2002), corresponds to a proper distance of 920 kpc. If the DLA lay this far behind the QSO, its expected surface brightness would decrease by a factor of ~ 7 but its illuminated size would nearly double. The predicted Lyman-α flux would be consistent with our observations as long

Regardless of the origin of the line, we can conclude that this DLA has a size of at least $\sim 1\farcs5$. If $1\farcs5$ is the typical radius of DLAs, then their observed number per unit redshift interval, $dN/dz \sim 0.2$ (e.g., Boissier, Péroux, & Pettini 2003), corresponds to a comoving number density of $\sim 10^{-1}h^3$ Mpc^{-3}. The average QSO would therefore have ~ 1 DLA within $1.3h^{-1}$ Mpc (i.e., $1'$ projected) if DLAs and QSOs were spatially uncorrelated and ~ 18 within the same radius if the QSO-DLA correlation function were similar to the QSO-LBG correlation function, $\xi(r) \sim (r/5h^{-1}\mathrm{Mpc})^{-1.6}$ (Adelberger & Steidel 2005).[7] Fluorescing systems similar to the one we have observed should therefore be common if QSOs live longer than a few Myr and optically thick clouds are not destroyed by their radiation. Systematic surveys for them (e.g., Moller, Warren, & Fynbo 1998; Fynbo et al. 2000; Francis & Bland-Hawthorn 2004) should provide interesting constraints on the lifetimes of QSOs and the nature of intergalactic clouds.

as the DLA were somewhat larger than we have assumed. In this case the implied length of the QSO lifetime would be $\gtrsim 6$ Myr. If the DLA lay in front of the QSO by 920 kpc, however, only a small fraction of its illuminated surface would be visible to us and the flux would be far lower than we have observed.

[7] Including optically thick clouds with lower (i.e., sub-DLA) column densities would increase the numbers significantly, although these clouds might not survive for long near the QSO.

KLA was educated by his discussions with T. Abel, A. Gould, M. Rauch, D. Weinberg, and (especially) J. Miralda-Escudé, who suggested a power-law density profile for intergalactic clouds and pointed out that it implied equation A1. R. Simcoe tracked down a raw HIRES spectrum and confirmed the redshift of HS1549+1919. We are grateful to our collaborators D. Erb, M. Pettini, and A. Shapley for their enormous contributions to our ongoing survey.

APPENDIX

RESPONSE OF A DLA TO A BLAST OF RADIATION

In the text we assumed that the ionization front from the QSO would advance most of the way to the center of the DLA, that the DLA would not glow brightly in Lyman-α until the ionization front was close to its final radius, and that the rest-frame equivalent width of fluorescent Lyman-α would be at least 200–300Å unless the continuum received a contribution from some other source. The last two assumptions should be true in general. The first will be true if the gas is smooth and centrally concentrated but may be false otherwise. Our reasoning is illustrated below with a simple physical model. Please recall that observed damped Lyman-α systems show a wide range of kinematic properties, from the simple to the clumpy and complex (e.g., Prochaska & Wolfe 1997; Prochaska & Wolfe 1998). The model's predictions should not be taken as anything other than a very rough guide.

We begin with a brief overview of the physical situation. Before it is struck by radiation from the QSO, the hydrogen at the optically thick edge of the DLA will presumably be in rough thermal and ionization equilibrium with the ambient radiation field, recombining as fast as it is ionized and emitting energy as fast as energy is absorbed. If the QSO has the same spectrum as the ambient background, its radiation will increase both the heating and ionization rates by the same factor $g \sim 2000$, driving the cloud wildly out of equilibrium.[8] An ionization front will advance into the cloud. At first the recently ionized material will not be able to cool from its initial temperature of ~ 50000K (Abel & Haehnelt 1999). The front will advance until it encounters material dense enough to recombine as fast as it is ionized. It will stall. The cooling rate will now exceed the heating rate, and the ionized material will cool until it reaches the same temperature it had before the radiation blast arrived.[9] The cloud will finally arrive at the equilibrium situation envisioned by Gould & Weinberg (1996).

Stalling Radius

We estimate the stalling radius for the ionization front by assuming that the cloud is centrally concentrated, with a mean density profile that varies with radius as $r^{-\gamma}$. In this case the integrated recombination rate for all the material exterior to radius r along a column of fixed cross-section is proportional to $r^{1-2\gamma}$. An increase in the ionization rate by a factor of g will be balanced by recombinations only when the radius has shrunk by the factor

$$\frac{r_{\rm initial}}{r_{\rm final}} = g^{1/(2\gamma-1)}, \tag{A1}$$

or ~ 13 if $g \sim 2000$ and the cloud has an isothermal profile (i.e., $\gamma = 2$). The QSO radiation that is pointed directly at the center of the DLA will therefore advance most of the way to the center before it stalls. If the initial ionized edge of the DLA lies at a radius of $1\farcs5$, the stalling radius will be $\sim 0\farcs1$. Since the recombination rate (and hence Lyman-α luminosity) is proportional to $g(r/r_{\rm final})^{-(2\gamma-1)}$ when the ionization front is at radius r, and $2\gamma - 1 \sim 3$, the Lyman-α emission will not be bright enough for easy detection until the ionization front is quite close to its stalling radius. We conclude that the separation between the Lyman-α fluorescence and the center of the DLA is unlikely to

[8] The factor $g \sim 2000$, derived in the main body of the text, is appropriate for a DLA that lies 0.38 proper Mpc from a QSO with the magnitude of HS1549+1919.

[9] Since the heating and ionization rates depend on density in the same way and on temperature in different ways, and since (according to our assumptions) each is increased by the same factor g when the QSO's radiation arrives, the initial and final equilibrium temperatures must be the same.

be resolvable from the ground. Clumping in the gas will not alter this conclusion as long as the strength of clumping $\langle\rho^2(r)\rangle/\langle\rho(r)\rangle^2$ does not depend strongly on r.

Stalling time

The same model provides a rough estimate of the time required for the cloud to reach its new equilibrium. Since the column density of material exterior to radius r is proportional to $r^{1-\gamma}$, the QSO will have to ionize a neutral hydrogen column of $N_{\rm HI} = N_i[(r_{\rm final}/r_{\rm initial})^{1-\gamma} - 1] = N_i[g^{(\gamma-1)/(2\gamma-1)} - 1]$ as it advances from the initial to the final radius. N_i, the total (neutral plus ionized) hydrogen column density exterior to $r_{\rm initial}$, is likely to be roughly 10^{20} cm^{-2}, since the optically thick edge of the cloud has a neutral hydrogen column density of $N_{\rm HI} \sim 10^{17}$ cm^{-2} and the typical neutral fraction at this radius is $\sim 10^{-3}$ (Zheng & Miralda-Escudé 2002a). Because the ionization rate is $\dot{N}_{\rm HI} = gF_c^0$, where F_c^0 is the inward flux of hydrogen-ionizing photons (cm^{-2} s^{-1}) in the ambient radiation field (equation 2), the rough time scale for reaching the equilibrium radius is $t_{\rm grow} \sim N_{\rm HI}/\dot{N}_{\rm HI} \sim g^{-\gamma/(2\gamma-1)} N_i/F_c^0$ for $g \gg 1$. The required time is $t_{\rm grow} \sim 1.2 \times 10^5$ yr for $g = 2000$, $N_i = 10^{20}$ cm^{-2}, and $F_c^0 = 1.6 \times 10^5$cm^{-2} s^{-1}. This is almost short enough to ignore in the present case, but could be significant for DLAs that are less intensely illuminated. Uncertainties in N_i mean that this time-scale should not be ignored in general. Clumping in the gas does not alter the expected value of $t_{\rm grow}$ but causes its actual value vary randomly among different rays towards the center of the DLA. These variations could be large for DLAs with significant sub-structure.

Temperature and Lyman-α equivalent width

In ionization equilibrium, the photoionization rate at radius r will equal the recombination rate at the same radius. Most Lyman-continuum photons will therefore be absorbed in regions with low neutral fraction ($\sim$ 0.01–0.1), since these are the regions with the highest recombination rates. The energy of the Lyman-continuum photons will have to be dissipated by mostly ionized gas. Assume momentarily that the gas is completely ionized. In this case, recombination and Brehmsstrahlung would be the main cooling processes at the relevant range of densities and temperatures. According to the rate coefficients collected in Tables 1 and 2 of Katz, Weinberg, & Hernquist (1996), energy losses from H and He recombination will exceed those from Brehmsstrahlung by a factor of around $\sim$ 2–3, with the exact factor depending on the temperature and on the dominant ionization state of He. These same coefficients imply that the time-scale $t_{\rm cool} \equiv E/\dot{E}$ for recombination cooling should be 2–3 times the recombination time-scale $t_{\rm rec} \equiv n_{\rm HII}/\dot{n}_{\rm HII}$. Since the recombination time-scale is proportional to $r^\gamma T^{0.7}$, and had initial value $t_{\rm rec} \sim N_i/\zeta \sim 20$Myr, the cooling time at the stalling radius for completely ionized gas is 2–3 times longer than $20g^{-\gamma/(2\gamma-1)}(T_s/T_i)^{0.7}$ Myr, or $t_{\rm cool} \sim 1$ Myr. Here $T_i \sim 10000$K and $T_s \sim 50000$K are the temperatures in the ionized skin of the DLA before and after the QSO's radiation arrives. Figure 1 of Katz et al. (1996) shows that line cooling is roughly two orders of magnitude faster than recombination cooling for predominantly neutral gas at these temperatures, and so the actual cooling time could be significantly shorter than 1 Myr if (as seems likely) the residual neutral fraction in the absorbing gas is greater than ~ 0.01. We conclude that the gas is likely to have reached a nearly equilibrium temperature, but uncertainties in N_i mean that one should not always assume that this is the case.

Because recombination cooling proceeds 2–3 times faster than Brehmsstrahlung cooling, roughly 70% of the energy absorbed from Lyman-continuum photons would be carried out of the cloud by recombination photons if the absorbing gas were completely ionized. With 40% of the escaping recombination energy in the form of Lyman-α photons (Gould & Weinberg 1996), the Lyman-α luminosity would equal $\sim 30\%$ of the absorbed Lyman-continuum luminosity in this case. Gould & Weinberg (1996) show that the fraction rises to $\sim 50\%$ if the absorbing gas is predominantly neutral. The actual fraction will be bracketed by these two values. The remaining energy will emerge either in other H/He recombination lines or in a continuum produced by two-photon decay and by the first (i.e., free-bound) photons of the recombination cascades. Much of this remaining energy will emerge in the wavelength range $1100 \lesssim \lambda/\text{Å} \lesssim 2000$ (i.e., 6–11 eV) covered by our G and $\mathcal{R}$ broad-band images, but even if all of it were concentrated in that range it would not be enough relative to Lyman-α to explain the relatively small observed equivalent width of the Lyman-α line. This conclusion holds equally well for smooth and clumpy gas.

REFERENCES

Abel, T. & Haehnelt, M.G. 1999, ApJL, 520, 13
Adelberger, K.L. 2004, ApJ, 612, 706
Adelberger, K.L. & Steidel, C.C. 2005, ApJ, in press (astro-ph/0505210)
Bergeron, J., Petitjean, P., Cristiani, S., Arnouts, S., Bresolin, F., & Fasano, G. 1999, A& A, 343, 40
Boissier, S., Péroux, C., & Pettini, M. 2003, MNRAS, 338, 131
Bunker, A., Smith, J., Spinrad, H., Stern, D., & Warren, S. 2003, Ap& SS, 284, 357
Cantalupo, S., Porciani, C., Lilly, S.J., & Miniati, F. 2005, ApJ, in press (astro-ph/0504015)
Francis, P.J. & Bland-Hawthorn, J. 2004, MNRAS, 353, 301
Francis, P.J., Palunas, P., Teplitz, H.I., Williger, G.M., & Woodgate, B.E. 2004, ApL, 614, 75
Fynbo, J.U., Thomsen, B., & Moller, P. 2000, A& A, 353, 457
Gould, A. & Weinberg, D.H. 1996, ApJ, 468, 462
Haehnelt, M.G., Steinmetz, M., & Rauch, M. 2000, ApJ, 534, 594
Hogan, C.J. & Weymann, R.J. 1987, MNRAS, 225, 1
Katz, N., Weinberg, D.H., & Hernquist, L. 1996, ApJS, 105, 19
McDonald, P. & Miralda-Escudé, J. 1999, ApJ, 519, 486
Moller, P., Warren, S.J., & Pynbo, J.U. 1998, A& A, 330, 19
Moller, P., Fynbo, J.P.U., & Fall, S.M. 2004, A& A, 422, 33
Osterbrock, D.E. 1962, ApJ, 135, 195
Prochaska, J.X. & Wolfe, A.M. 1997, ApJ, 487, 73
Prochaska, J.X. & Wolfe, A.M. 1998, ApJ, 507, 113
Richards, G.T., Vanden Berk, D.E., Reichard, T.A., Hall, P.B., Schneider, D.P., SubbaRao, M., Thakar, A.R., & York, D.G., 2002, AJ, 124, 1
Steidel, C.C., Adelberger, K.L., Shapley, A.E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel, C.C., Shapley, A.E., Pettini, M., Adelberger, K.L., Erb, D.K., Reddy, N.A., & Hunt, M.P. 2004, ApJ, 604, 534

Urbaniak, J.J. & Wolfe, A.M. 1981, ApJ, 244, 406
Weidinger, M., Moller, P., Fynbo, J.P.U., & Thomsen, B. 2005, A&A, 436, 825
Zanstra, H. 1949, BAN, 11, 1
Zheng, Z. & Miralda-Escudé, J. 2002a, ApJL, 568, 71
Zheng, Z. & Miralda-Escudé, J. 2002b, ApJ, 578, 33